Fiber Based Dispersion Compensation Schemes in Nonlinear Fibers for Laser Diode Pulses in High Bit-Rate IM/DD Systems

A. Sánchez-Díaz[1], P. García-Fernández[1], J.M. Soto-Crespo[2] and C.R. Mirasso[3]

1- Instituto de Estructura de la Materia, CSIC, Serrano 123.

2- Instituto de Óptica, CSIC, Serrano 121, 28006 Madrid, Spain.

3- Departamento de Física, Universitat de les Illes Balears, 07071 Palma de Mallorca, Spain.

Abstract

The combined effects of chromatic dispersion and self-phase modulation are numerically investigated for a 10 Gbit/s IM/DD system over 100 km of standard single-mode fiber for input signals modeled by stochastic rate equations for single-mode semiconductor lasers. The signal degradation and filtering effects are studied through the monitoring of the eye opening penalty (EOP). It is observed that the shape of the input signal, which depends on the laser parameters, has a major influence on the EOP. Fiber based pre- and post-compensation schemes are compared for different values of the lasers parameters and compensation length. In most cases, pre-compensation yields lower eye-opening penalty for the laser pulses analysed.

I. Introduction

The introduction of the Erbium-doped fiber amplifier (EDFA) has brought high capacity optical networks operating around 1550 nm a large step closer to reality. The ultimate transmission limitations are now laser chirp, chromatic dispersion, fiber nonlinearities and noise from EDFAs. Since the majority of today installed fiber (standard single-mode fiber) is designed to operate around 1310 nm, the minimum dispersion region, large efforts are made to commercially exploit and upgrade it by using 1550 nm lasers and dispersion compensation schemes [1].

The eye opening of intensity modulated (IM) signals is critically dependent on the combined effects of second order chromatic dispersion (so called Group Velocity Dispersion, GVD) and self-phase modulation (SPM), due to the Kerr effect. This is well known for long-haul systems with direct detection (DD). Yet, most investigations focus on zero dispersion systems [2] and only a few investigators have considered transmission on standard single-mode (SSM) fibers [1,3] with lasers operating at 1550 nm. Several mechanisms have been proposed to compensate chromatic dispersion in SSM fibers. The most straightforward is the addition to the system of a piece of fiber with opposite GVD. In another approach, the optical spectrum is inverted by optical phase conjugation near the center of the system, so that the dispersion in the second half of the system compensates for the dispersion in the first half [4,5,6]. Pre- and post-compensation using dispersion shifted fibers and optical phase conjugation seem to be the most promising techniques.

Pulse propagation in optical fibers is well described by the non-linear Schrödinger equation (NLSE). This equation takes into account the effects of the group velocity dispersion and the nonlinearity of the fiber (SPM). When one of these effects is negligible, the NLSE can be easily solved for any initial condition either in the spectral or in the time space [7]. Otherwise, numerics becomes necessary.

The optical pulse is usually modeled as Gaussian [7] or Supergaussian [1,2,7]. To our knowledge, one of the few works that uses the rate equations of the laser diode to generate the optical pulse is the one of Suzuki and Ozeki [8]. They studied the effect of Group Velocity Dispersion (GVD) and Self Phase Modulation (SPM) not in SSM fibers but in dispersion shifted fibers (DSF).

Light pulses generated by directly modulated semiconductor lasers have several features, in particular the modulation-induced frequency chirp, which increases the spectral content of the pulse. It is the aim of this paper to analyse the eye opening degradation in the propagation of these light pulses which can present a large frequency chirp.

The effect of semiconductor laser noise in optical communication systems was reviewed in [9]. When the laser is directly modulated by varying the injection current, intensity and phase fluctuations, as well as timing jitter [10], limit the performance of communication systems working at GHz rate. The randomness of the turn-on time of the optical pulse is originated by intrinsic spontaneous emission noise, amplifying the non-linear dynamics the indeterminacy of the turn-on time. In particular, changes in the laser output intensity cause changes in the lasing frequency through associated changes in the number of carriers, leading to a chirp of frequency [11]. This kind of behaviour can be observed, for example, when modulating the laser in the non-return to zero (NRZ) scheme. At larger times after the switch on, the evolution of the system is characterised by relaxation oscillations of the intensity and carrier number. During the oscillations the laser output can greatly exceed its steady-state value, and as a consequence, the associated frequency chirping can be very large. The relatively large fluctuations in the amplitude and phase caused by spontaneous emission noise before the intensity reaches a macroscopic value clearly indicate that a deterministic analysis of the system evolution has a limited validity. We have considered stochastic evolution equations based in the Langevin formulation of the rate equations for a single mode semiconductor laser [12].

In this paper we compare two fiber based compensation schemes for chromatic dispersion when the input signal is coming out from a directly modulated 1.55 μm semiconductor laser, modeled by stochastic rate equations. In one case, the compensation is done before the basic link (pre-compensation) and in other case, the dispersion compensation scheme is applied after the basic link (post-compensation). The basic link is a 10 Gbit/s NRZ channel over 100 km SSM fiber.

The paper is organized as follows: in section two we provide a description of the theoretical model used in our problem. In section three we draw our attention to the results given by the numerical simulations with special interest in the effects due to filters and different bias currents. In section four we focus on pre- and post-compensation. Finally, in section five we review the main conclusions of the present work.

II. Theoretical model

The optical source is assumed to produce a biased IM signal with a NRZ format. This signal is obtained by numerical simulation of the noise driven rate equations as in ref. [10]. We have numerically integrated the rate equations for the slowly varying amplitude of the electric field (E) and carriers number (N) inside the laser cavity for a DFB SMSL (Distributed Feed-Back Single Mode Semiconductor Laser), which read

$$\frac{dE}{dt} = \frac{1-i\alpha}{2}\left(\frac{g(N-N_\circ)}{\sqrt{1+s|E|^2}} - \gamma_p\right)E(t) + \sqrt{2\beta N}\xi(t), \tag{1}$$

$$\frac{dN}{dt} = \frac{I(t)}{e} - \gamma_e N - \frac{g(N-N_\circ)}{\sqrt{1+s|E|^2}}|E|^2, \tag{2}$$

where $\xi(t)$ is a white Gaussian process taking into account spontaneous emission, with zero mean and a correlation given by $<\xi(t)\xi^*(t')>= 2\delta(t-t')$, g is the differential gain, γ_p, the inverse photon lifetime, γ_e, the inverse carrier lifetime, I, the injected current, β, the spontaneous emission rate, N_o, the carrier number at transparency, s, the inverse saturation intensity and α, the linewidth enhancement factor. Typical values for these parameters are: g=3 $\times 10^{-8}$ ps^{-1}, $\gamma_p = 0.5$ ps^{-1}, $\gamma_e = 5 \times 10^{-4}$ ps^{-1}, $\beta = 5 \times 10^{-9}$ ps^{-1}, N_o=1.5$\times 10^8$, s=5$\times 10^{-7}$ (adimensional) and $\alpha = 0$, 2 or 4. I(t) follows a square wave form of maximum value I_{on} during the period of modulation $T_m = 100$ ps for a "1" bit and I_{bias} for a "0" bit. In our case I_{on} takes values in the interval 2.0 to $3.5 \times I_{th}$ ($I_{th} = 13.35$ mA) while I_{bias} =1.0 to $1.5 \times I_{th}$. The laser chirp is monitored by the linewidth enhancement factor α which varies from 1.5 to 8 in semiconductor lasers [13].

We consider a 10 Gbit/s system over 100 km of SSM fiber with GVD, laser chirp and SPM for input peak powers from 6.2 to 12.8 mW which correspond to a I_{on} in the range 2.0 to $3.5 \times I_{th}$ and different linewidth enhancement factor. The laser wavelength is 1.55 μm and we consider pseudorandom word modulation (PRWM) in the NRZ scheme. It has been shown [10] that in the case of the return-to-zero (RZ) format for frequencies larger than 2 GHz, timing jitter and the dispersion in the maximum output photon number become larger when biasing above threshold than below. This is due to the existence of pattern dependence effects. In that case, a special value for the bias current exists. For such value, the response of the system is almost independent on previous bits. This bias current is slightly below threshold and the response of the system is almost the same under periodic modulation or PRWM. In the NRZ scheme and for a frequency of 10 Gbits/s this special bias current does not exist. In our work we have studied the effects of several bias currents above threshold measuring the effects of the propagation through the EOP (Eye-Opening Penalty).

The propagation is governed by the generalized nonlinear Schrödinger equation [7], which reads

$$i\frac{\partial E}{\partial z} = -\frac{i}{2}\Gamma E + \frac{1}{2}\beta_2\frac{\partial^2 E}{\partial T^2} - \gamma|E|^2 E\,, \tag{3}$$

where E(z,T) is the complex slowly varying amplitude field, z is the propagation distance and T is the time in a reference frame moving at the group velocity. γ is the nonlinear parameter that takes account of the optical Kerr effect, Γ, the losses which are perfectly compensated by the EDFA's and neglected in our study, β_2, the dispersion parameter. Typical values are $\gamma = 2 \times 10^{-3}$ km^{-1} mW^{-1}, $\Gamma = 0.2$ dB/km, $\beta_2 = -16$ ps^2 km^{-1}. The split-step Fourier method [7] is used to solve equation (3).

We have analysed the different results obtained due to the inclusion of one lowpass second order Butterworth filter [2,3] (with a 3 dB bandwidth equals to 13 GHz) at the fiber input, output or at both places. We will remark that the best configuration corresponds to the latter one. In addition, the optical second order Butterworth filter, placed at the fibre input, can be implemented by means of a photorefractive fibre grating [14, 15].

The bit sequence is sampled after the lowpass filter at the maximal eye opening. A power penalty is usually defined as 10 log(a/b) where a and b are the maximal eye openings measured before and after the fiber link respectively. This eye-opening penalty (EOP) is used to investigate the combined effects of chirp from the transmitter laser (represented by the linewidth enhancement factor α), chromatic dispersion (GVD) and SPM.

SPM alters the phase, and hence the instantaneous frequency of the weak and intense parts of the pulse by unequal amounts, i.e., the propagating signal experiences a self-chirp. Moreover, there is an interplay between laser chirp, chromatic dispersion, SPM-induced chirp and the effect of filtering. This complex scenario yields pulse spreading or pulse compression, depending mainly on the magnitude of the input peak power, line enhancement factor (laser chirp) and filtering.

III. Effect of the bias current and filtering

First, we investigate the effects of the filters in the absence of compensation. As an example, in figure 1 we show the eye pattern considering a filter at the fiber input, output or at both places for $\alpha = 4$, $I_{bias} = 1.2 I_{th}$ and $I_{on} = 2.8 I_{th}$ for $\alpha = 4$ in nonlinear propagation. We observe that the best EOP corresponds to place one filter at the fiber input and output. This fact is reasonable since the chirp increase the spectral content of the pulse. Therefore, filtering the input has a positive effect because it reduces the spectral width of the pulse. On the other hand, the benefits of filtering the output are well known [1,2,3]. As expected, we have checked that in the free chirp case ($\alpha = 0$) there is no appreciable difference between the eye patterns with filters at the fiber input and output or simply one filter at the output.

Consequently, in all the cases in which compensation is not used we will place two filters at the fiber input and output. It must be noted that if the filters are not included the eye is always closed after a propagation of 100 km.

We have also investigated the influence of the linewidth enhancement factor α and the bias current without compensation for a fiber length of 100 km. Figure 2 shows the EOP for different bias current (1.0, 1.2 and 1.4 I_{th}) as a function of the input peak power including a second order Butterworth filter before and after the fiber link. We remark that the used I_{on} goes from 2.0 to $3.5I_{th}$ since for lower injection currents the ratio between the maximum power for a bit "1" and "0" is small and after the propagation the eye is closed. In addition, for the cases with higher chirp, the EOP decreases as the input power increases while for the cases with lower chirp (α = 2, 0) the opposite happens. We observe that for the case of $I_{bias} = I_{th}$ with α =2 and 4, the EOP increases until a certain peak power after which it begins to decrease although the EOP for α =2 increases again in the last values of the power interval. On the other hand, for $I_{bias} = 1.2I_{th}$ (1.1 and 1.3 show the same behaviour), the EOP for $\alpha = 2$ and zero chirp ($\alpha = 0$) displays similar traces: it always grows with the power but remains under the $\alpha = 4$ case although the traces tend to converge to the same value. For $I_{bias} = 1.4I_{th}$, the case with $\alpha = 4$ is always below an EOP of 2 dB and does not show a decreasing behaviour beyond an input peak power while the plots for α =0, 2 increase monotonously. Similar results have been found for the last studied bias current, $I_{bias} = 1.5I_{th}$. According to these results the most stressing feature regards the fact that the EOP can decrease as a function of the input peak power for intermediate bias currents and with an appropriate chirp ($\alpha = 4$ with $I_{bias} = 1.2I_{th}$). We have also shown that the EOP for $\alpha = 0$ and 2 are very similar, therefore the only case with a significative chirp corresponds to $\alpha = 4$.

In figure 3 we analyse the EOP curves in the linear and nonlinear propagation for three bias currents. In principle, one would expect that the nonlinear effects, which are larger as we increase the input peak power, would play a beneficial role in the propagation and therefore the EOP should decrease with the input peak power. The figure 3 shows in fact that the form of the pulse in the input signal is the most determinant factor in the EOP curves. As an example the EOP plots for $\alpha = 4$ decrease with the input peak power in the linear and nonlinear cases. It must be noted that we are obtaining different input peak powers by varying the injected current I_{on} and subsequently the pulse shape. Moreover, for $\alpha = 4$ the nonlinear traces always lie below the linear ones while for $\alpha = 0$ happens the opposite. This behaviour can be explained through a partial compensation between laser chirp and SPM-induced chirp.

Figure 4 shows the EOP versus input peak power for (a) $\alpha = 4$, (b) $\alpha = 2$ and (c) $\alpha = 0$ using several bias currents. We can observe that for the highest chirp parameter ($\alpha = 4$) the best EOP corresponds to the largest currents while for $\alpha = 0$ the opposite happens. In addition, the figure shows two clearly separated bands, the lowest for $\alpha = 0$ and the highest for $\alpha = 4$. The one corresponding to $\alpha = 2$ is placed between the others but it is closer to the unchirped one. This intermediate behaviour can be explained cosidering, as was mentioned before, that for $\alpha = 2$ the chirp is not very important. However, the EOP traces in this case are not significative since they are placed in a narrow band around 0.5 dB.

Some additional comments arise about the bias current. In the case of RZ modulation (Return to Zero) the optimum bias current is always slightly below threshold for frequencies lower than 6 GHz [10]. Above this value, the time that the laser is on the "off" state is shorter and the field does not reach very small values so pattern effects due to the bit sample could be found. We are modulating in NRZ at 10 Gbit/s. In this case a *1 0 1 0 1 0* NRZ bit pattern is equivalent to a 5 Gbit/s RZ *1 1 1* pattern with a best bias current for $I_{bias} = 0.98 I_{th}$. The problem is that for two subsequent bits "1" the pulse intensity decays from a value close to the stationary one which is usually considerably smaller than the pulse maximum and therefore the optimum bias current is not fixed (supposing that exists) but depends on the bit sequence. We have chosen $I_{bias} = 1.2 I_{th}$ because it gives an intermediate EOP for the cases of higher chirp and lower chirp (see figure 4). Moreover, a high bias current is not desirable since it produces that the level corresponding to the bits "0" becomes closer to the bits "1". On the other hand, the remaining bias currents are very near to the threshold value.

IV. Pre- and post-compensation

Now we draw our attention to pre- and post-compensation by using dispersion shifted fibers [1,2] with $\beta_{2c} = +45\mathrm{ps}^2\mathrm{km}^{-1}$. In the linear case there is a length (L_c) for which the chromatic dispersion is completely compensated. This is achieved when

$$L_c\beta_{2c} + L\beta_2 = 0. \tag{4}$$

In our case, for a link of 100 km of SSM, $L_c = 35.55$ km. We have observed that the best results, i.e. lowest EOPs, occur for the two following configurations: filter at the input with post-compensation and pre-compensation with filter at the output. Consequently, we adopt this scheme in the rest of the paper

We have performed an extensive comparative study of the EOP in pre- and post-compensation for a number of compensation lengths, linewidth enhancement factors α and input peak powers. The results are summarised in figure 5, where IPP means the Input Peak Power measured at the laser output as it is done in the previous figures. We can distinguish between low chirp and high chirp cases. The plots for $\alpha = 0, 2$ show an increasing EOP as a function of the input power while for high chirp ($\alpha = 4$) the EOP tends to decrease in most cases when the input power grows. Such behaviour is similar to the one displayed in figure 2. Moreover, pre-compensation gives better EOP in most traces. This behaviour is understood taking into account that in this complex scenario the nonlinear effects are positive due to the partial compensation between chirp and SPM [16]. Thus, we have a good performance if we pre-compensate providing that the input signal is not filtered. Doing that, the peak power increases because the pulse is narrowed and subsequently the standard propagation can be considered more nonlinear. As an example, in figure 6 we have displayed the eye patterns for a pre-compensation and post-compensation with $I_{on} = 3.0 I_{th}$, $I_{bias} = 1.2 I_{th}$ and a $L_c = 30$ km.

Depending on the compensation length and power used the EOP is located below or above the uncompensated plot. In pre-compensation, for L_c lower than 40 km, the EOP is below the uncompensated case. In figure 5 we can see that in pre-compensation, only for $L_c = 40$ km and high input powers the corresponding EOP is higher than the one without compensation. It is worth noting that using post-compensation the distances for which the compensated EOP is greater than the uncompensated one are shorter. For example, with $\alpha = 0$, distances greater than 10 km and beyond a certain input power correspond to an EOP above the compensation-free trace. Something similar happens for $\alpha = 2$ and $\alpha = 4$. These results indicate that equation (4) simply gives a first approximation to our problem since it is only valid for linear propagation. Moreover, according to our simulations, an optimum compensation length can only be determined for all the input power range in the free-chirp case. In the remaining cases ($\alpha = 2, 4$) the optimum length depends on the power, specially for the highest chirp. However, this study is of high interest since we have achieved which are the compensation distances and powers (I_{on}) needed for getting an EOP below or very close to zero.

V. Conclusions

We have numerically investigated the combined effects of laser chirp, fiber dispersion and SPM for an IM/DD 10 Gbit/s DFB laser in the NRZ scheme over 100 km of SSM fiber. The effects of filtering have been studied in detail, obtaining that the best scheme for a good propagation performance without compensation corresponds to the use of two filters at the fiber input and output respectively while for compensation we must pre-compensate and filtering the output or filtering the input and post-compensate.

It has also been investigated the effects of the bias current on the EOP without compensation including two 3 dB second order low pass Butterworth filters at the fiber input and output respectively. We observed that for an intermediate range of bias currents (I_{bias} =1.1, 1.2 and 1.3I_{th}) the EOP with $\alpha = 4$ decreases as the input power increases while for the other chirp parameters ($\alpha = 0, 2$) the EOP always grows. In addition, we have observed that the most significative chirp corresponds to $\alpha = 4$ since $\alpha = 2, 0$ cases display a very similar behaviour.

The influence of nonlinear effects was studied yielding that, for high chirp ($\alpha = 4$), the nonlinearity plays a positive role. This fact is due to the partial compensation of laser chirp and SPM. On the other hand, the decreasing EOP traces as a function of the input peak power, in the linear and nonlinear fiber with $\alpha = 4$, are due to the modification of the pulse shape by varying the injected current I_{on}. In general we observed that the form of the input pulse, which is determined by the laser parameters, has a larger influence on the EOP that GVD and SPM.

Finally, the simulations show that the power penalty due to the combined effects of chirp, dispersion and SPM can be suppressed by properly designed pre-compensation of the chromatic dispersion, resulting in a negative EOP for some input powers, compensation lengths and a laser chirp corresponding to $\alpha = 2$. We remark that in our study pre-compensation is much better than post-compensation for obtaining low EOP, while in other cases, for example when using Supergaussian pulses [1] (with a different chirp behaviour that yields compression in the normal dispersion regime), post-compensation is the best scheme.

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FIGURE CAPTIONS

- **Fig. 1(a-d).** Four trains of 28 pulses each in a time interval of 400 ps with $\alpha = 4$, $I_{bias} = 1.2I_{th}$ and $I_{on} = 2.8I_{th}$. **(a)** laser output. **(b)** plot obtained after 100 km of SSM fiber with a second order Butterworth filter at the fiber input. **(c)** the same as **(b)** with the filter placed at the fiber exit. **(d)** the same case but with two filters at the fiber input and output.

- **Fig. 2(a-c).** Eye Opening Penalty (EOP) versus Input Peak Power (dBm) for **(a)** $I_{bias} = I_{th}$, **(b)** $I_{bias} = 1.2I_{th}$ and **(c)** $I_{bias} = 1.4I_{th}$. Diamonds $\alpha = 4$, triangles $\alpha = 2$ and squares $\alpha = 0$.

- **Fig. 3(a-c).** EOP (dB) versus Input Peak Power (dBm) comparing the linear and nonlinear cases for **(a)** $I_{bias} = I_{th}$, **(b)** $I_{bias} = 1.2I_{th}$ and **(c)** $I_{bias} = 1.4I_{th}$. Diamonds correspond to a linear fiber and stars to a nonlinear fiber, with $\alpha = 4$. Squares, linear fiber and triangles, nonlinear fiber, for $\alpha = 0$.

- **Fig. 4(a-c).** Comparison beween the EOP (dB) versus the Input Peak Power for different chirps: **(a)** $\alpha = 4$, **(b)** $\alpha = 2$, **(c)** $\alpha = 0$. Crosses $I_{bias} = 1.1I_{th}$, stars $I_{bias} = 1.2I_{th}$, squares $I_{bias} = 1.3I_{th}$, diamonds $I_{bias} = 1.4I_{th}$ and triangles $I_{bias} = 1.5I_{th}$.

- **Fig. 5(a-f).** EOP (dB) versus the Input Peak Power for different chirp parameters and $I_{bias} = 1.2I_{th}$. **(a)** pre-compensation and **(b)** post-compensation for $\alpha = 0$. **(c)** pre-compensation and **(d)** post-compensation for $\alpha = 2$. **(e)** pre-compensation and **(f)** post-compensation for $\alpha = 4$. Diamonds correspond to $L_c = 10$ km, triangles to $L_c = 20$ km, squares to $L_c = 30$ km, crosses to $L_c = 40$ km and stars to the uncompensated case.

- **Fig. 6(a-d).** Four trains of 28 pulses each in a time interval of 400 ps with $\alpha = 4$, $I_{bias} = 1.2I_{th}$, $I_{on} = 3.0I_{th}$ and $L_c = 30$ km. **(a)** laser output for pre-compensation. **(b)** plot obtained after 100 km of SSM fiber and 30 km of pre-compensation with a second order Butterworth filter at the fiber output. **(c)** the same as **(a)** but for post-compensation. **(d)** plot obtained after 100 km of SSM fiber and 30 km of post-compensation with a second order Butterworth filter at the fiber input.